# Neutron skins,nucleon knockout and new polarized target technologies

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Prof S Ducket (Chemistry)

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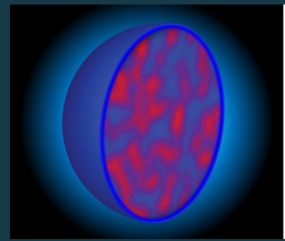
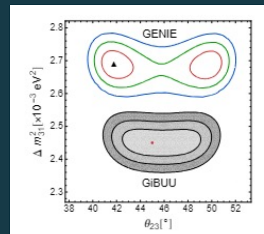
# Outline



- Cohπ method for $^{208}$Pb neutron skin; status of $^{40}$Ca/$^{48}$Ca measurement

- Nuclear physics constraints for next generation neutrino facilties




Many-proton knockout from $^{12}$C with CLAS@JLAB

E4nu via A(e,e’X) (A=D,C,Ar) with CLAS12@JLAB

- Early York R&D for achieving room temperature liquid polarised target media at the intensity frontier

# Neutron skins

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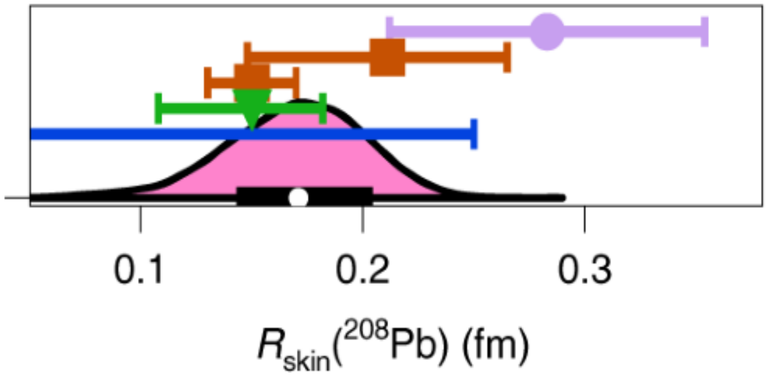
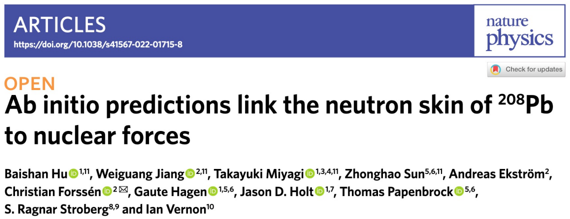
# Neutron skins from Coherent pion photoproduction





ARTICLES
https://doi.org/10.1038/s41567-022-01715-8
nature physics
Check for updates

OPEN
**Ab initio predictions link the neutron skin of $^{208}$Pb to nuclear forces**

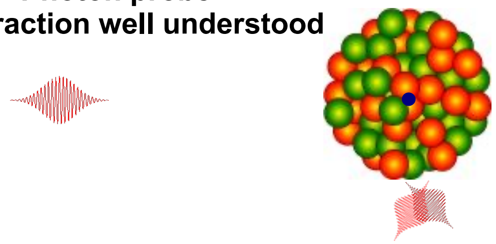
Baishan Hu[1,11], Weiguang Jiang[2,11], Takayuki Miyagi[1,3,4,11], Zhonghao Sun[5,6,11], Andreas Ekström[2], Christian Forssén[2], Gaute Hagen[1,5,6], Jason D. Holt[1,7], Thomas Papenbrock[5,6], S. Ragnar Stroberg[8,9] and Ian Vernon[10]

Neutron skins from Coherent $\pi$ photoproduction
Tarbert, DPW et. al., PRL **112, 242502 (2014)**

NEW $^{48}$Ca and $^{40}$Ca currently under analysis

# Coherent pion photoproduction in PWIA

Photon probe ✓
Interaction well understood



$\pi^0$ meson – produced with ~equal probability on protons *AND* neutrons.

Reconstruct $\pi^0$ from $\pi^0 \rightarrow 2\gamma$ decay

- Angular distribution of $\pi^0$ $\rightarrow$ PWIA contains the matter form factor

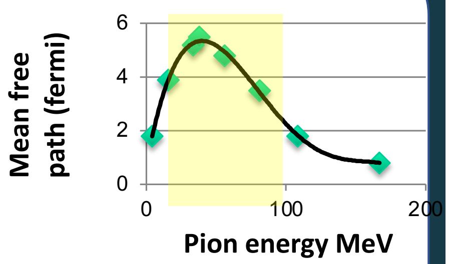
$$d\sigma/d\Omega(\text{PWIA}) = (s/m_N^2)\, A^2\, (q_\pi^*/2k_\gamma)\, F_2(E_\gamma^*,\theta_\pi^*)^2\, |F_m(q)|^2 \sin^2\theta_\pi^*$$

- $|F_m(q)|^2$ – **Matter** form factor

- For full calculation : ISI - Negligible
  FSI - Weak where skin extracted (mfp ~5 fm! ).

**s** – square of total energy of $\gamma$-N pair [MeV$^2$]
**q** – Momentum transfer [MeV/c] **F$_2$** - spin independent amplitude (MAID PWA)

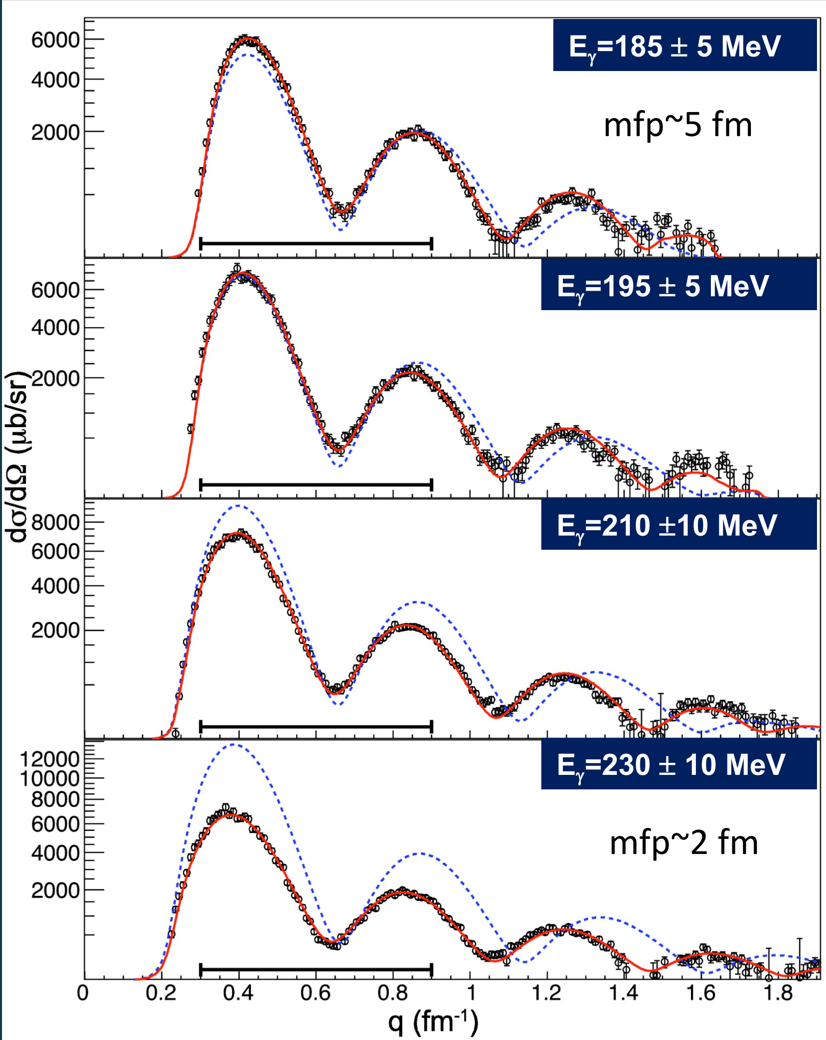
Crystal Ball detector (A2@MAMI)




From predictions of Mecking PLB 103B p401 (1981)

# $^{208}Pb(\gamma,\pi^0)$ Momentum transfer distributions

Square root scale




-- PWIA calculation

– Full calculation

Drechsel, Kamalov, Tiator et. al. NPA 660 (1999)

**Fitting procedure**

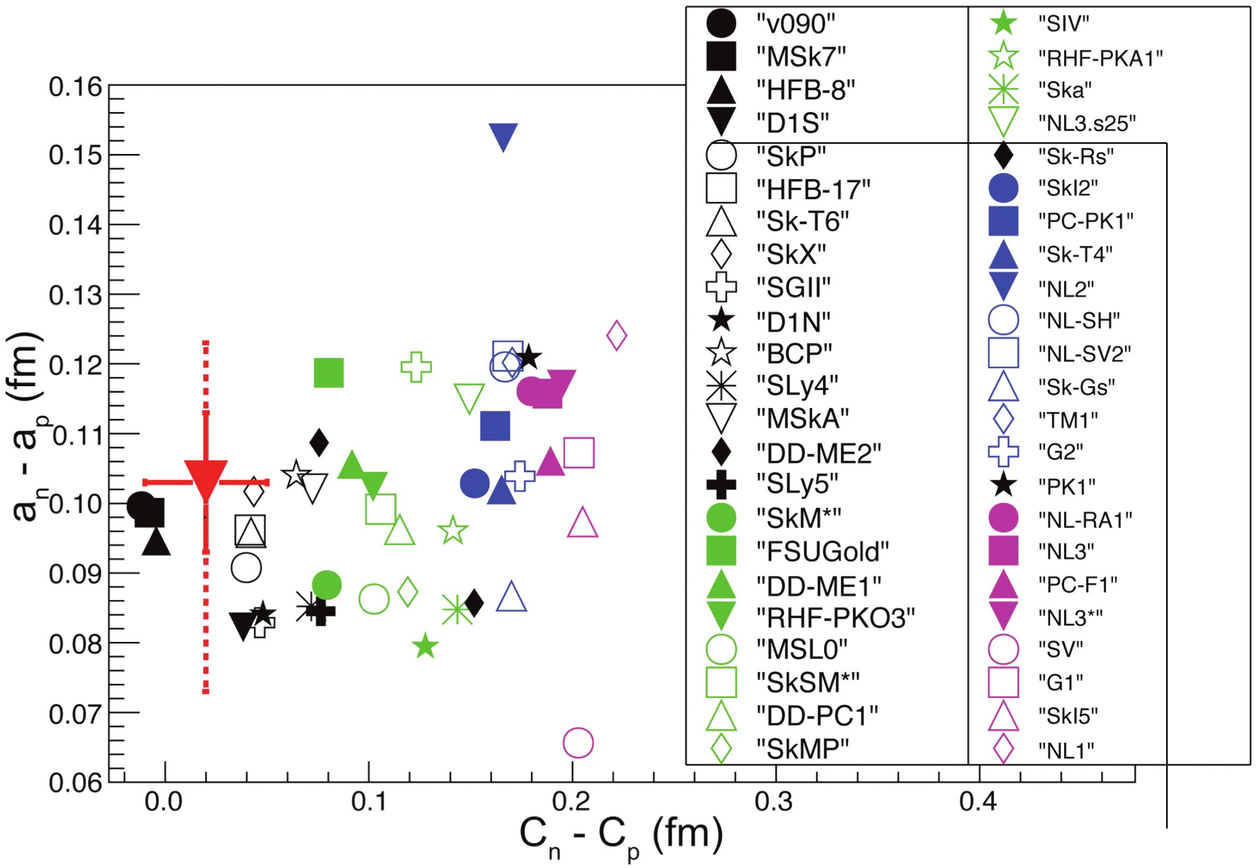
Calculate grid $c_n$=6.28-7.07 fm
$a_n$=0.35-0.65 fm

Predictions smeared by *q* resolution

Interpolated fit to experimental data (*q* = 0.3 - 0.9)

Free param. : norm, $c_n$, $a_n$,
Fixed param. : $c_p$=6.68 $a_p$= 0.447
(PRC 76 014211 (2011))

**Information on the shape** of the FF is used in the method
However, the data and model agreed on absolute scale
to within 5% (comp[arable with the experimental systematic)




Theory data from 2PF analysis of range of functionals (Centelles, Barcelona)

$$\rho(r) = \frac{\rho_0}{1+\exp\left(\frac{r-c}{a}\right)}$$

$$\Delta r_{np} = 0.15 \pm 0.03(\text{stat.})^{+0.01}_{-0.03}(\text{sys.})\ \text{fm}$$

**Systematic error is in the fitting of the model to the data. It is not an estimated "theory" systematic**

# Miler critique on Coh$\pi$ theory

PHYSICAL REVIEW C **100**, 044608 (2019)

**Coherent-nuclear pion photoproduction and neutron radii**

Gerald A. Miller
*University of Washington, Seattle, Washington 98195-1560, USA*

Complex $\pi$-A optical potential in DKT theory neglects 2nd order CEFSI

Miller calculated the effect of including CEFSI
- Negligible effect on minima/maxima positions (0.001 fm$^{-1}$ for 1st min)
- Increase in cross section of order 5%
- Small effect on shape (±**0.5** % change in rel 1st, 2nd maxima heights)

Miller estimates systematic by varying the neutron diffuseness such that **absolute** cross sections in the maxima agree with/without CEFSI
-> Skin with this modification in less tension with PREX result

$$\Delta r_{np} = 0.23 \pm 0.03\,(\text{stat.})^{+0.02}_{-0.03}\,(\text{sys.}) \pm 0.07(\text{th.sys.})\,\text{fm}.$$

**However - this is not the method employed in Tarbert et. al**
Using absolute cross sections (measured to ~±5%) rather than FF shape is a non-starter

The CEFSI induced 0.5% change in FF shape (with unaltered minima/maxima positions) would not significantly change the extracted skin

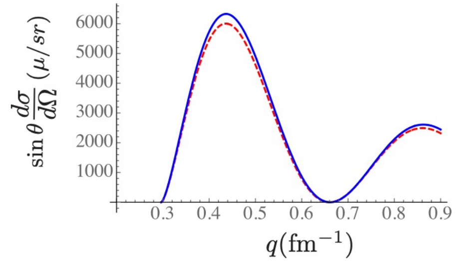



FIG. 3. Cross section as a function of momentum transfer $\Delta q \equiv |\mathbf{k} - \mathbf{q}|$. Solid (blue) is the complete calculation including the one-body and two-body terms. Dashed (red) includes one-body only.

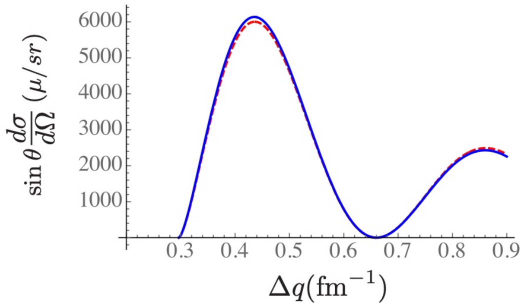
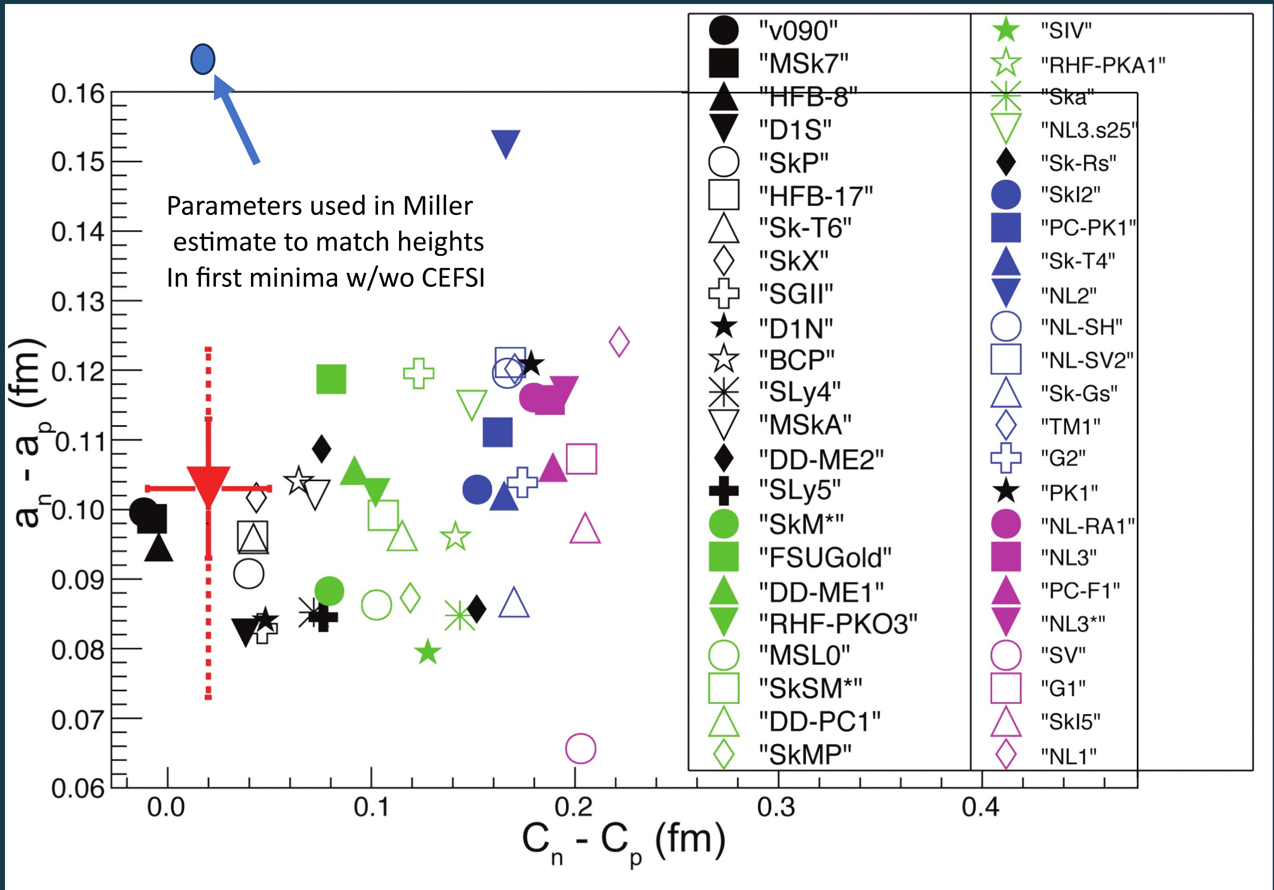
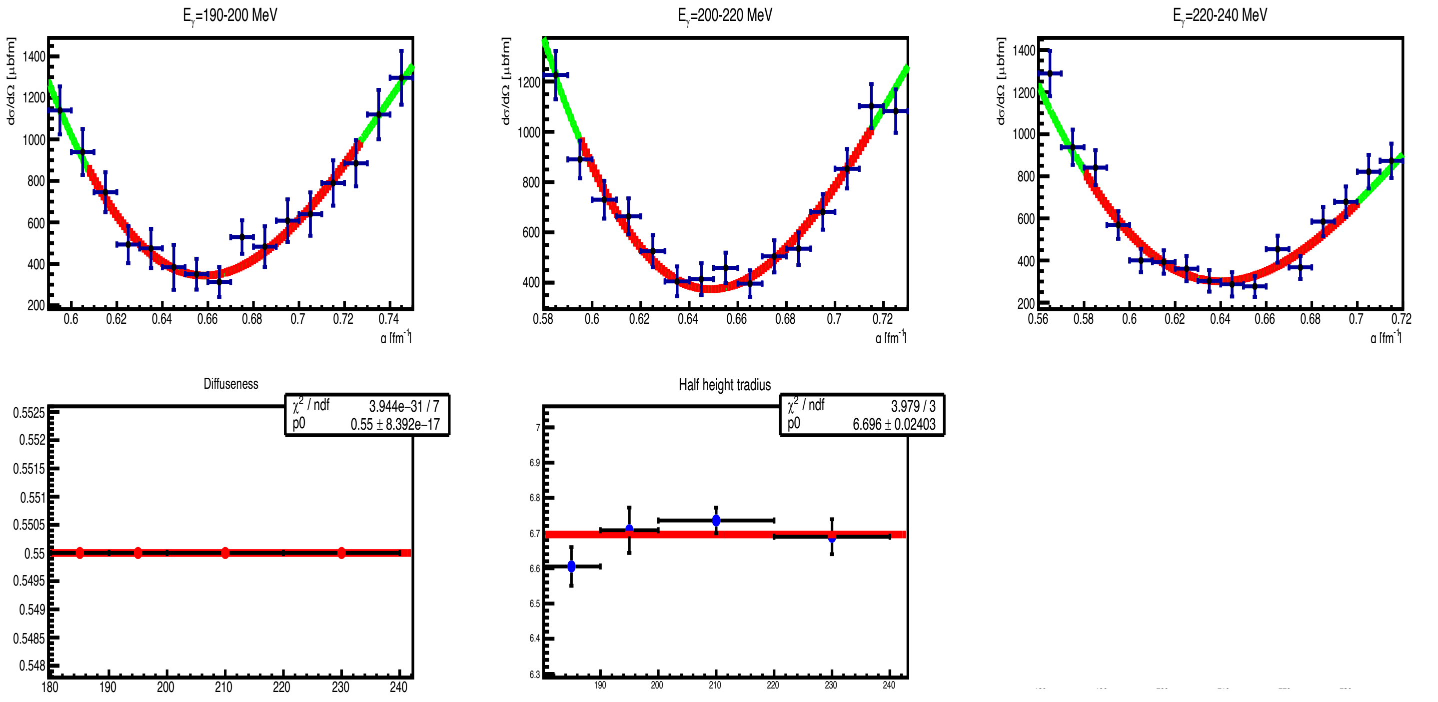



FIG. 5. Cross section as a function of momentum transfer $q$. Solid (blue) is the complete calculation including the one-body and two-body terms. Dashed (red) includes one-body only with $a_n =$ 0.61 fm

# Miler critique on Cohπ theory



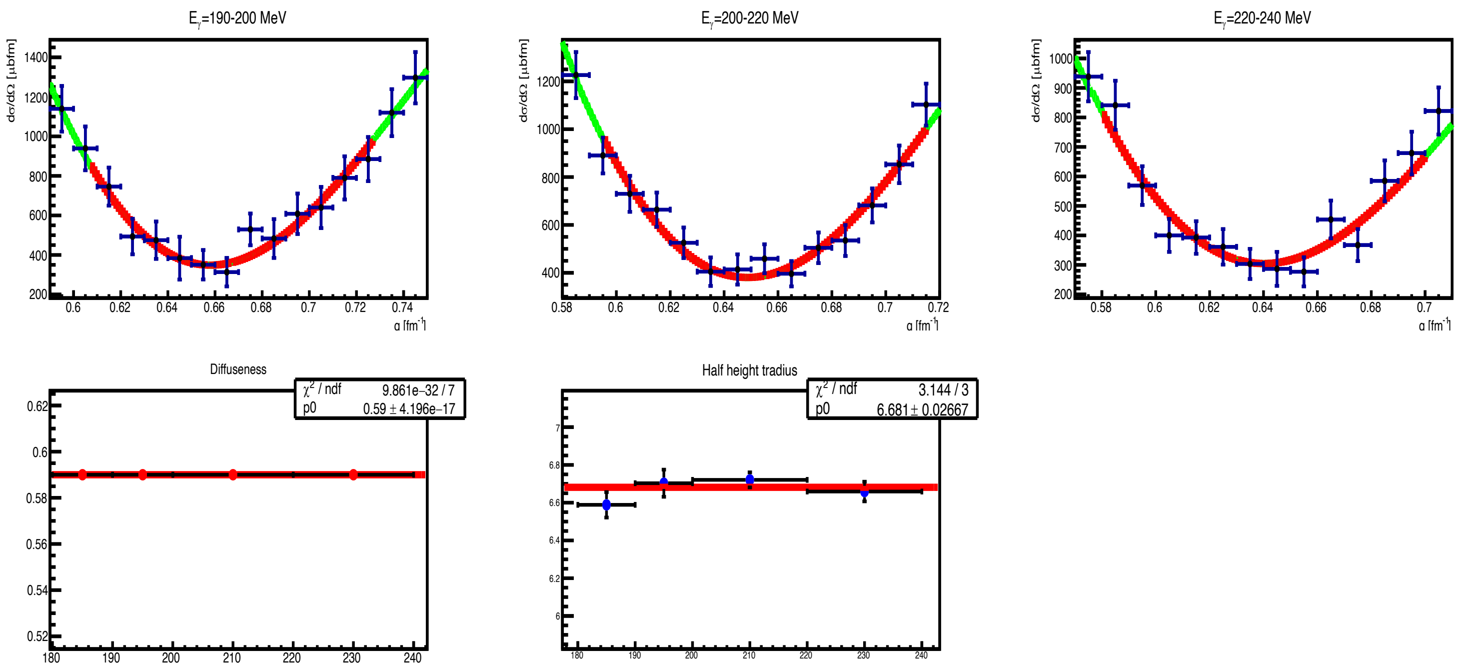
# $1^{st}$ minima fits: Fixed $a_n$ = 0.55




$r_{np}(a_n=0.55) = 0.14\pm0.02(\text{stat})$

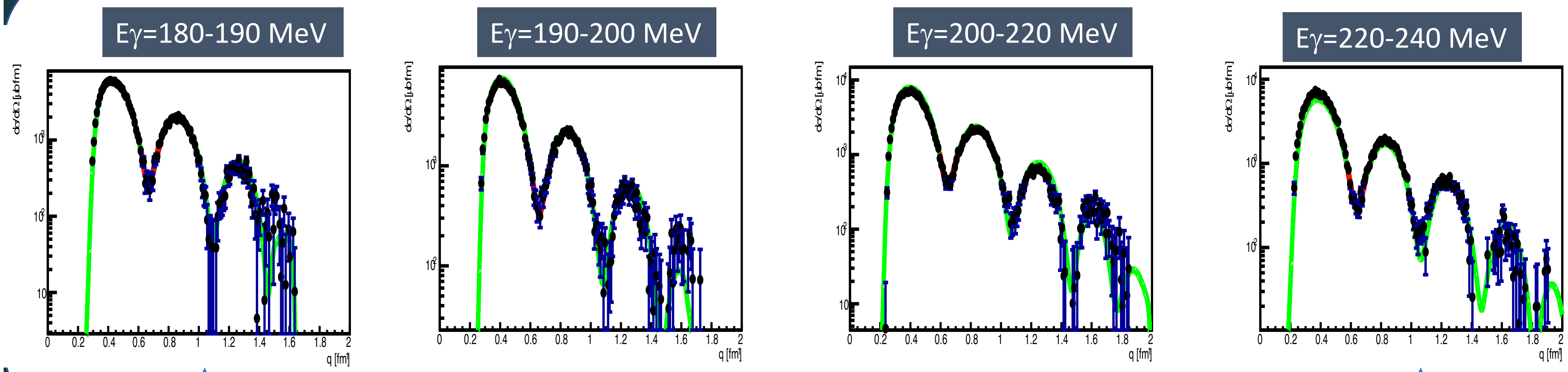
Stat error smaller than Tarbert et. al
- less data used but only fitting one parameter

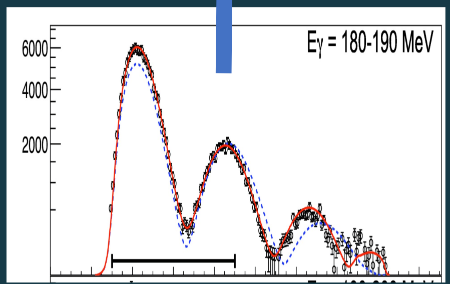
# $1^{st}$ minima fits: Fixed $a_n = 0.59$

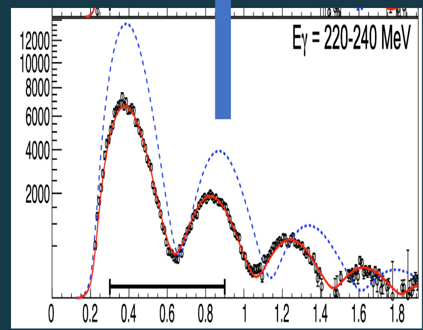



$r_{np}(a_n=0.59) = 0.18 \pm 0.02(\text{stat})$

# Full FF : $a_n$ = 0.55 Fitted in 1st minima <u>only</u>




No significant deviations at high q
-> Even when FF determined **<u>only</u>** from 1st min.

FSI effects much stronger with increasing q
-> constraint on FSI aspects of model

# Other systematic studies

| Method | Diffuseness | Cn | Fitted range | skin |
|---|---|---|---|---|
| Analysis in Tarbert PRL | Free parameter | Free parameter | q=0.3-0.9 $Fm^{-1}$<br><br>Over 1st , 2nd maxima | 0.15 ± 0.03 (stat)$^{+0.01}_{-0.03}$ (sys) |
| Fixed diffuseness | 0.55 | Free parameter | 1st minima | 0.14 ±0.02 (stat) |
| Fixed diffuseness | 0.59 | Free parameter | 1st minima alone | 0.18 ±0.02 (stat) |
| Fixed diffuseness | 0.59 | Free parameter | 2nd minima alone | 0.18 ± 0.02 (stat) |
| Fixed diffuesness | 0.59 | Free parameter | Region of 3rd minima | 0.18 ± 0.02 (stat) |

Also - Consistent skin (within sys and stat errors) when fitting maxima only with fixed $a_n$

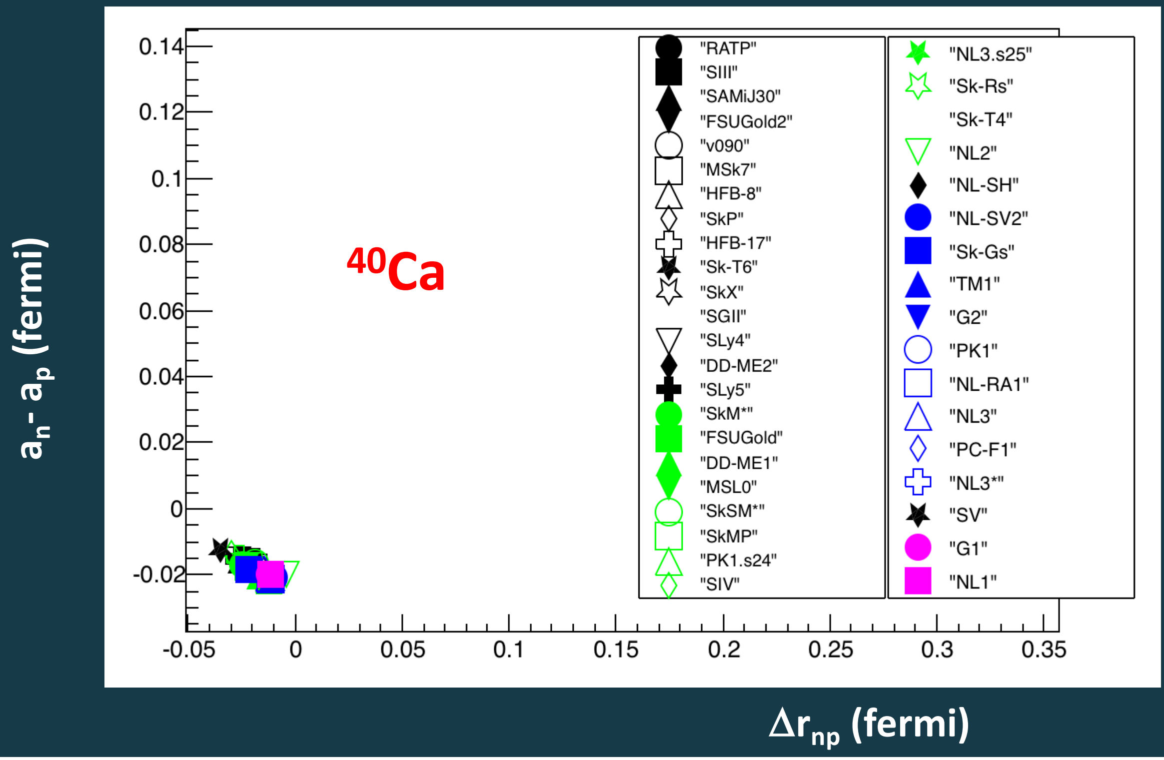
**The tension with PREX is not resolved by inclusion of CEFSI in Coh$\pi$ model**

We welcome theoretical developments – and are happy to apply them in the extraction

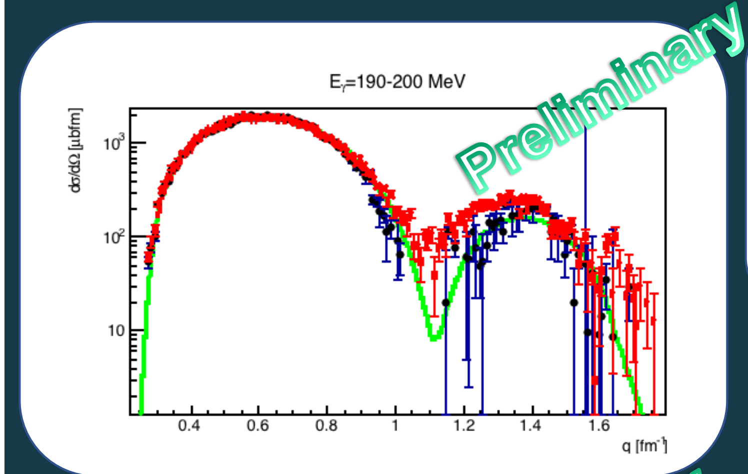
# $^{40}$Ca: A well understood challenge for Coh$\pi$ method

$^{40}$Ca - powerful check on systematics (expt. and theory) for Coh$\pi$ (and other) methods

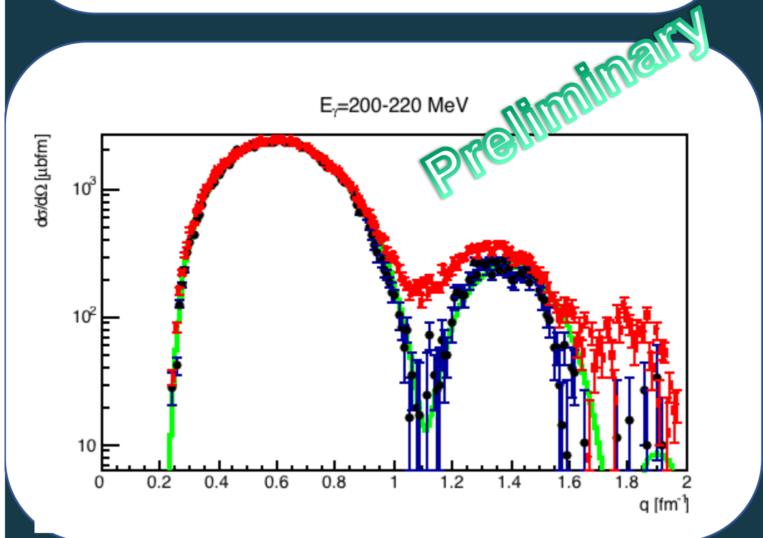
Theories agree  on skin to within ~0.02 fermi  – a “lighthouse” for the field

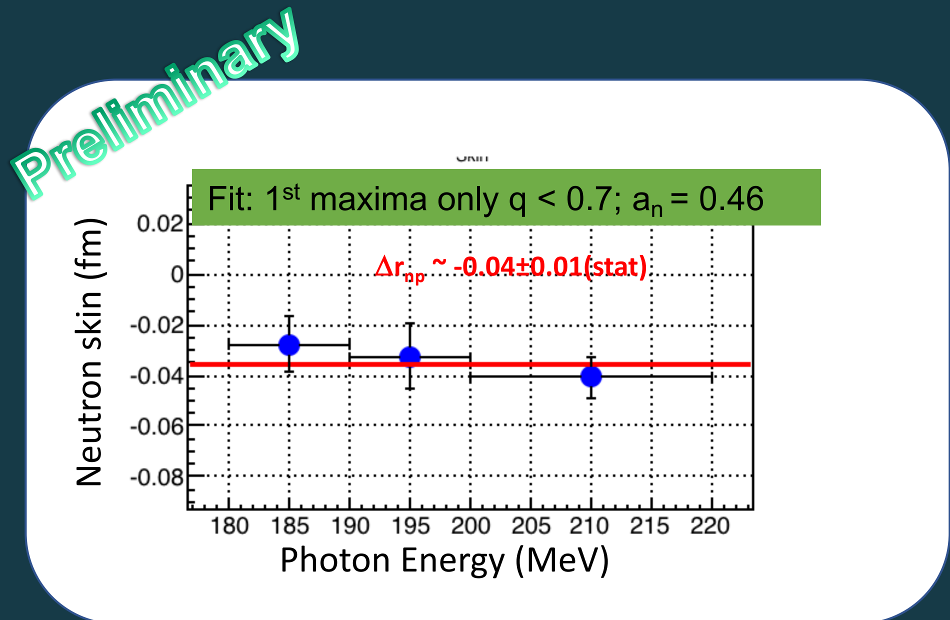



## $^{40}$Ca: Momentum transfer distributions (same beamtime as $^{208}$Pb)

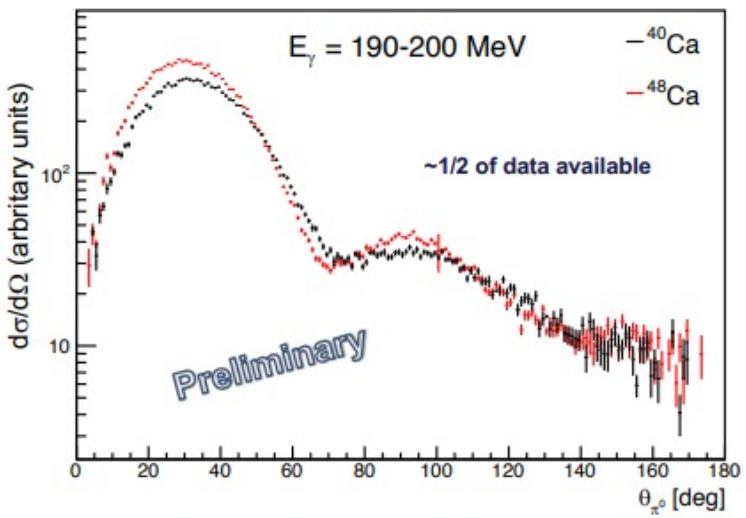


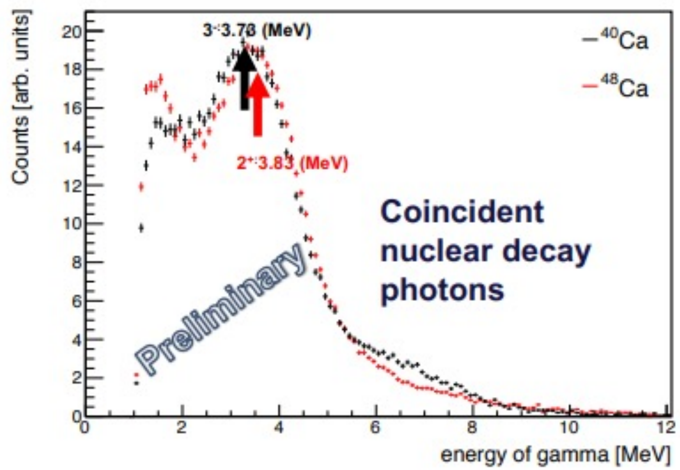

- QFPI background removed (missing energy)
- Additional ME fit to remove inelastic strength @ 3.74, 6.5MeV
- Model fit from 1st maxima only ($q<0.7\ fm^{-1}$)
  $c_p$ = 3.676 fm $a_p$=0.473fm (Brown, MSU)
  $a_n$=0.46 (average of theory)
  neutron skin + normalisation – free parameters

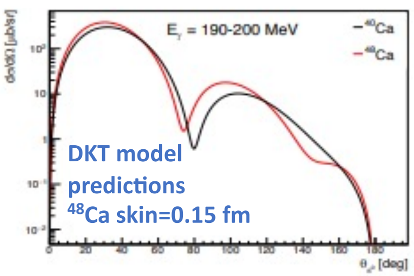


# $^{40}$Ca and $^{48}$Ca – New measurement, “raw“ results



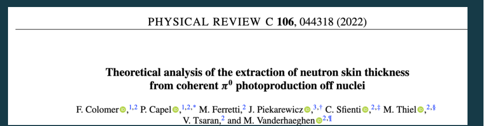




**!!! Caveats !!!**

Calibrations not complete, incoherent backgrounds/empty target not removed, detector acceptance crudely incorporated, …

We plan to publish both $^{40}$Ca measurements together (with $^{48}$Ca)

Charge distns in 40/48 are almost identical – sensitivity to neutron distribution clear in DKT model **and data**
Contradicts “complete insensitivity” of Cohπ production to neutron skins claimed in recent paper


PHYSICAL REVIEW C 106, 044318 (2022)

Theoretical analysis of the extraction of neutron skin thickness from coherent $\pi^0$ photoproduction off nuclei

F. Colomer, P. Capel, M. Ferretti, J. Piekarewicz, C. Sfienti, M. Thiel, V. Tsaran, and M. Vanderhaeghen

## Photo- and electro- induced nucleon knockout to constrain neutrino-nucleus modelling

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# Many proton knockout and neutrino physics

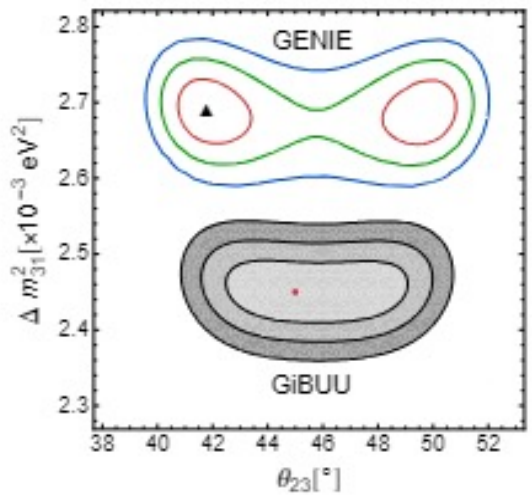
Next generation $\nu$-facilities e.g. DUNE,.. -> use A($\nu$,p) to determine incident $\nu$

Nuclear modelling -> Largest uncertainty in systematic error budget

e4$\nu$: Test modelling with EM induced knockout
-> Where we know the incident energy accurately

Photo-induced – $Q^2=0$
(removes uncertainty in $Q^2$ dependence of in-medium N*)

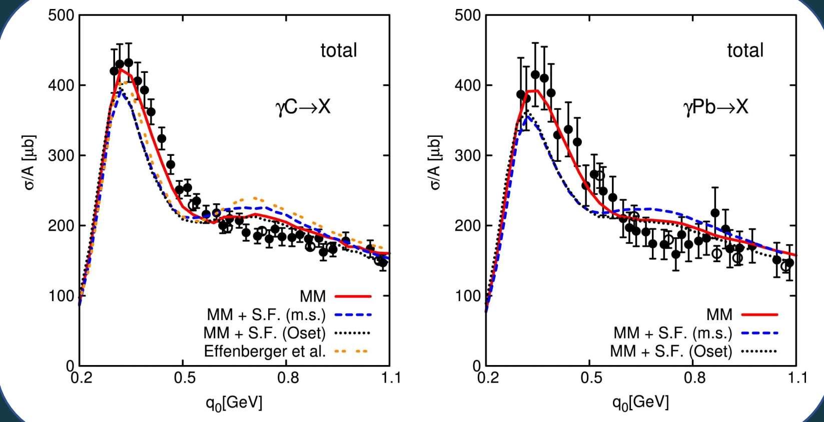
Electro-induced - $Q^2$ variable with reaction kinematics (e4$\nu$)



# GiBUU model

Unified theory and transport framework MeV and GeV scales

- Includes N* spectra, decay couplings (string models above resonance region)
- Models of medium modifications, …
- Hadrons propagate in mean field - scatter according to physics cross sections




Based on gradient expansion of Kadanoff-Baym eqn.

$$\frac{\partial(p_0-H)}{\partial p_\mu}\frac{\partial F(x,p)}{\partial x^\mu}-\frac{\partial(p_0-H)}{\partial x_\mu}\frac{\partial F(x,p)}{\partial p^\mu}=C(x,p)$$

Hamiltonian H

- Hadronic mean fields, Coulomb, "off-shell"

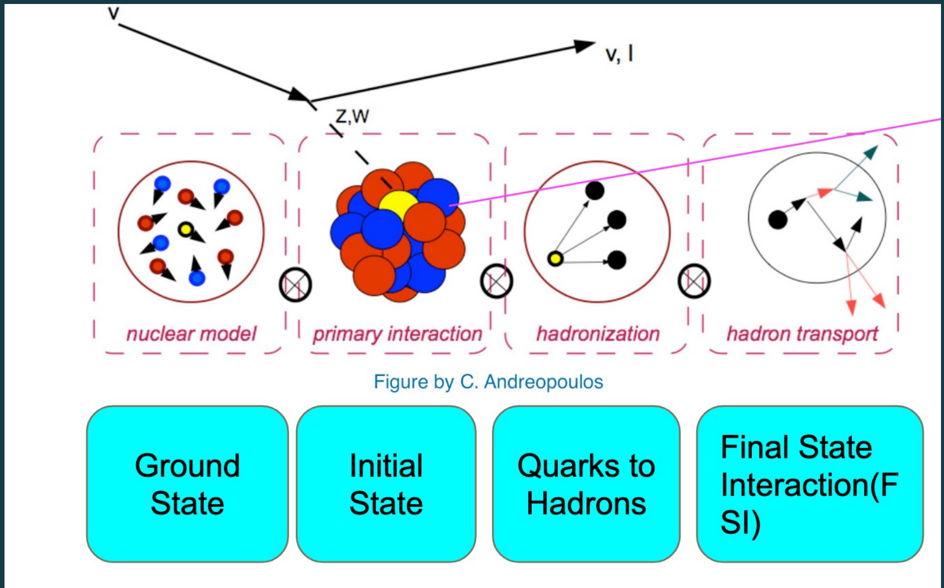
Collision term C(x,p)

- Decays and scattering processes (2- and 3- body)

🙁GiBUU Comprehensive but currently lacks 3-meson production, SRC/MEC convoluted (2p-2h parameterization from work of Bosted and Christy)

# GENIE model

Based on a factorization approach




Nuclear models – a range available e.g. Fermi gas with SRC

Intranuclear cascade model for FSI

For more details see https://hep.ph.liv.ac.uk/~costasa/genie/index.html

# Study of photo-induced reactions (CLAS@JLAB)

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# Experimental data - Jefferson Lab

Electron beams up to 12 GeV

Halls A,C electron scattering spectrometers

Hall B electron scattering (and historically real tagged photons) with large acceptance spectrometer

Hall D – photon beams and (planned ) neutral Kaon Beams with large acceptance Glue-X detector

# Experimental aspects

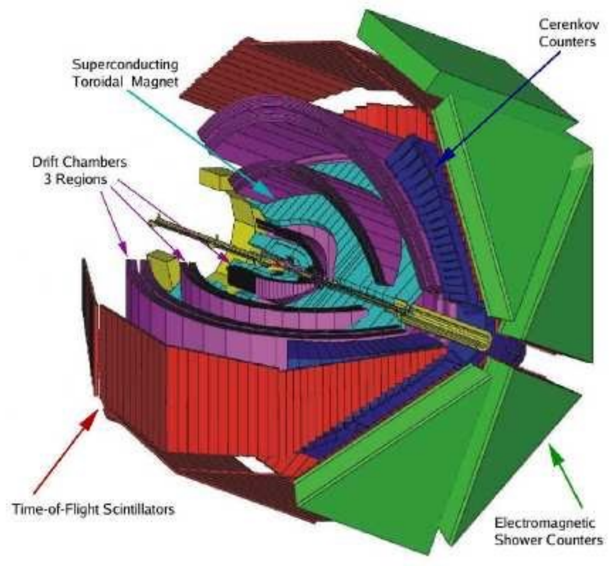
CLAS spectrometer - Toroidal magnetic field provided by 6 superconducting coils

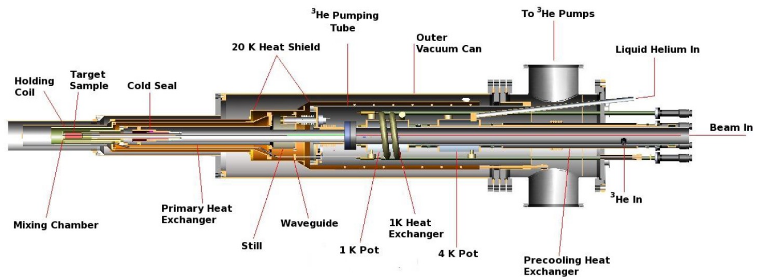
Instrumented with tracking, calorimetry, time-of flight, Cerenkov detectors.

~80% acceptance for single proton
Minimum momentum 0.4 GeV/c

Carbon containing targets included with FROST (frozen spin target - butanol) experiment

Measure: $^{12}C(\gamma,Xp)$ {X:1→6}

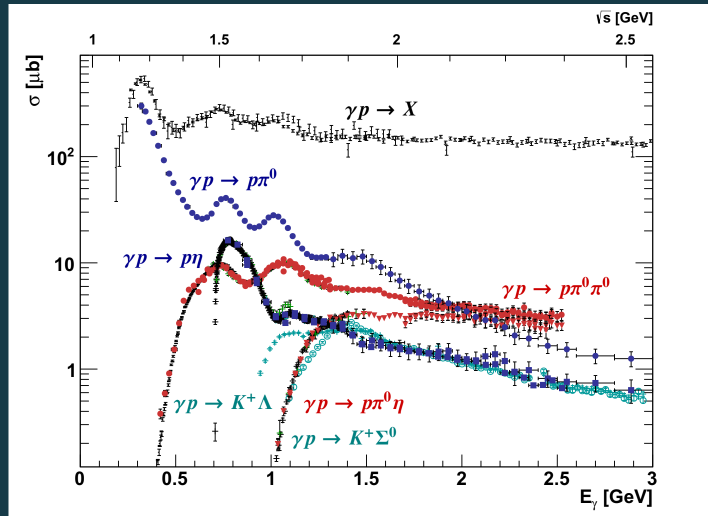


# What happens when ~GeV photon interacts with a nucleus?

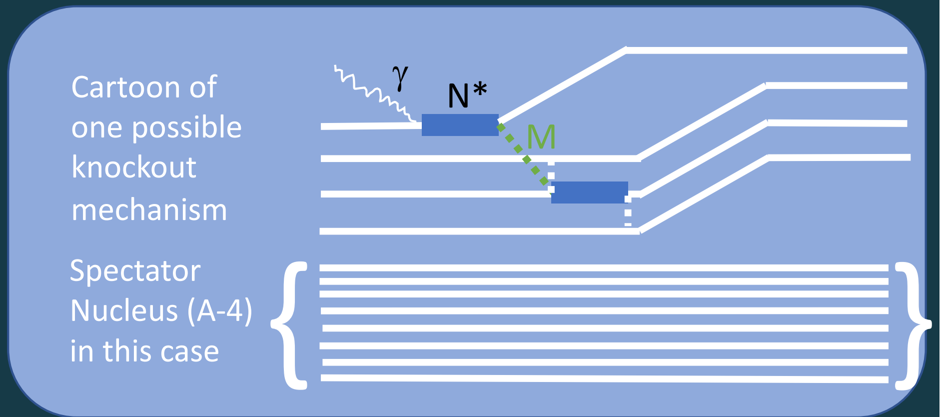
Main seed reaction is **meson photoproduction** off a nucleon (often via intermediate N*) -> nucleon knockout

- ➔ Recoiling nucleon from initial M production
- ➔ Subsequent (M,2N), (M,3N), …
- ➔ Subsequent (N,N')
- ➔ Heavier M add to multiplicity e.g. $\omega$->3$\pi$

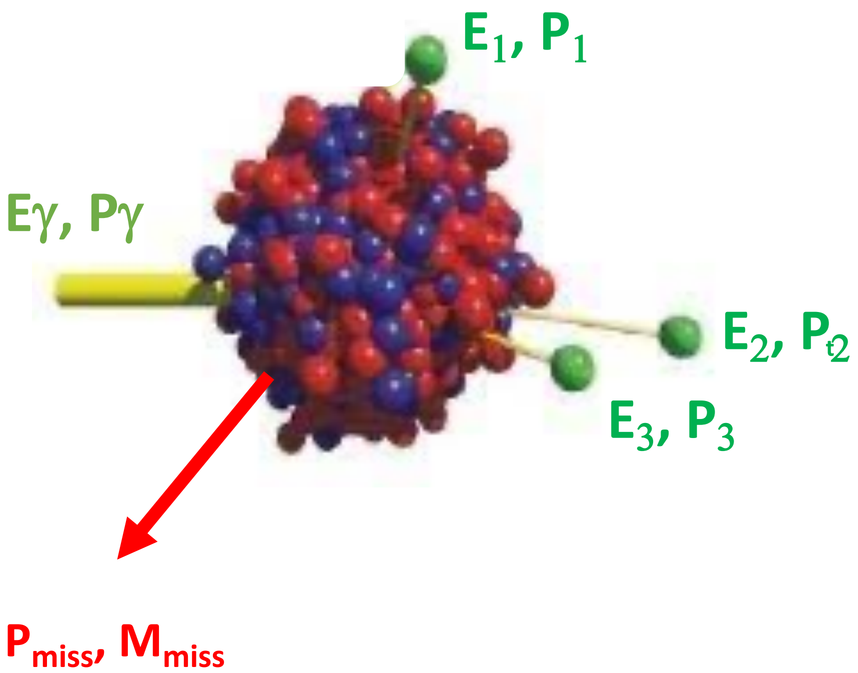



Also:

- ➔ Highly off-shell (high momenta) nucleonic components in 1B interactions (SRCs)
- ➔ Off-shell contributions (e.g. MEC, N*N->NN)



# Kinematic observables




$M^2_{Miss} = (E_\gamma + M_t)^2 - (P_\gamma + \Sigma P_{pi})^2$

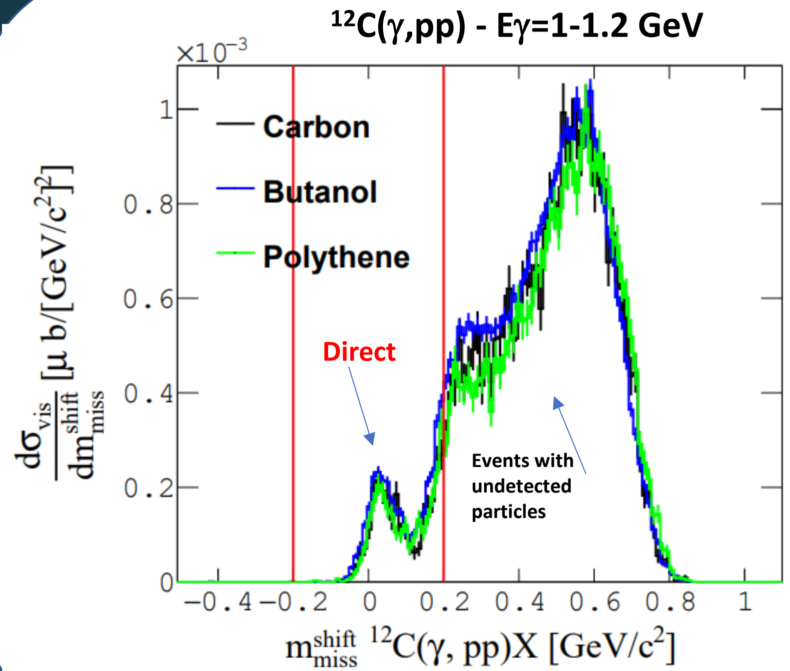
$M^2_{Miss}(\text{shift}) = M^2_{Miss} - M(A\text{-}i, Z\text{-}i)$

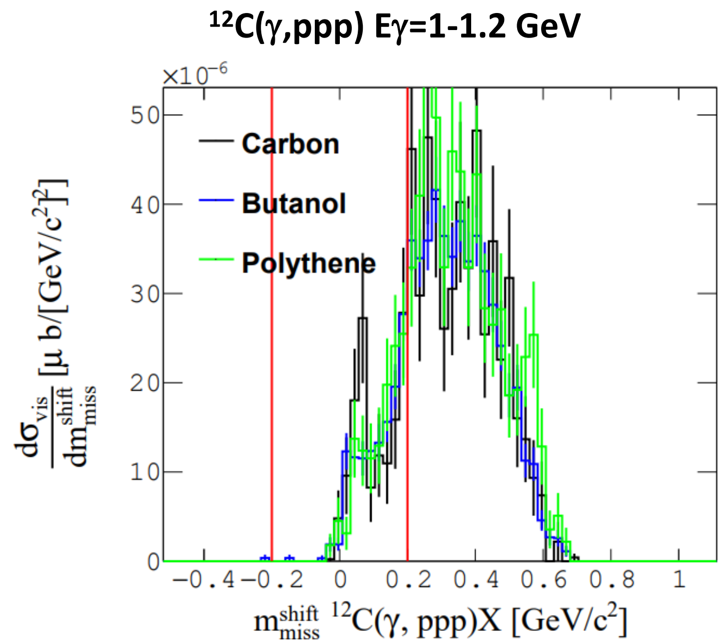
$\theta_{recoil}$ – Angle of recoil

$P^{perp}$ - Transverse momentum of recoil

GiBUU predictions passed through CLAS detector acceptance, resolutions and directly compared to data – “visible” cross section

# Missing mass in pp, ppp knockout

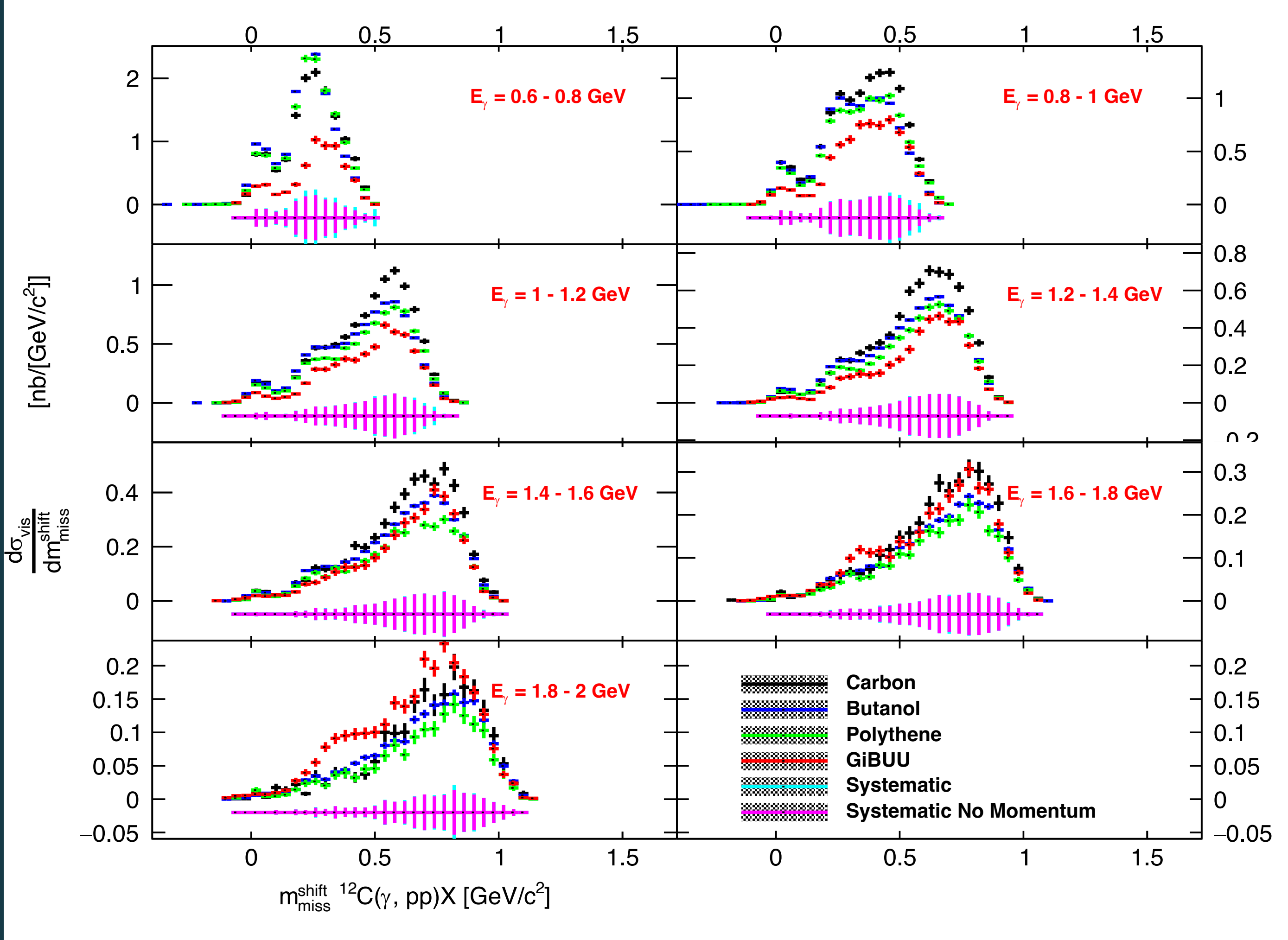



Direct (γ,pp) knockout from nuclei above A=4 never seen above ~0.4 GeV – and never with such clean separation
New challenge for models e.g. N*N->NN (and SRC?)
Data has cuts to enhance direct processes (recoil in central angular region, $P^{perp}$ < 0.2 GeV/c2 (Fermi range)

PhD analysis Williams (York)

# Missing mass – 2p knockout



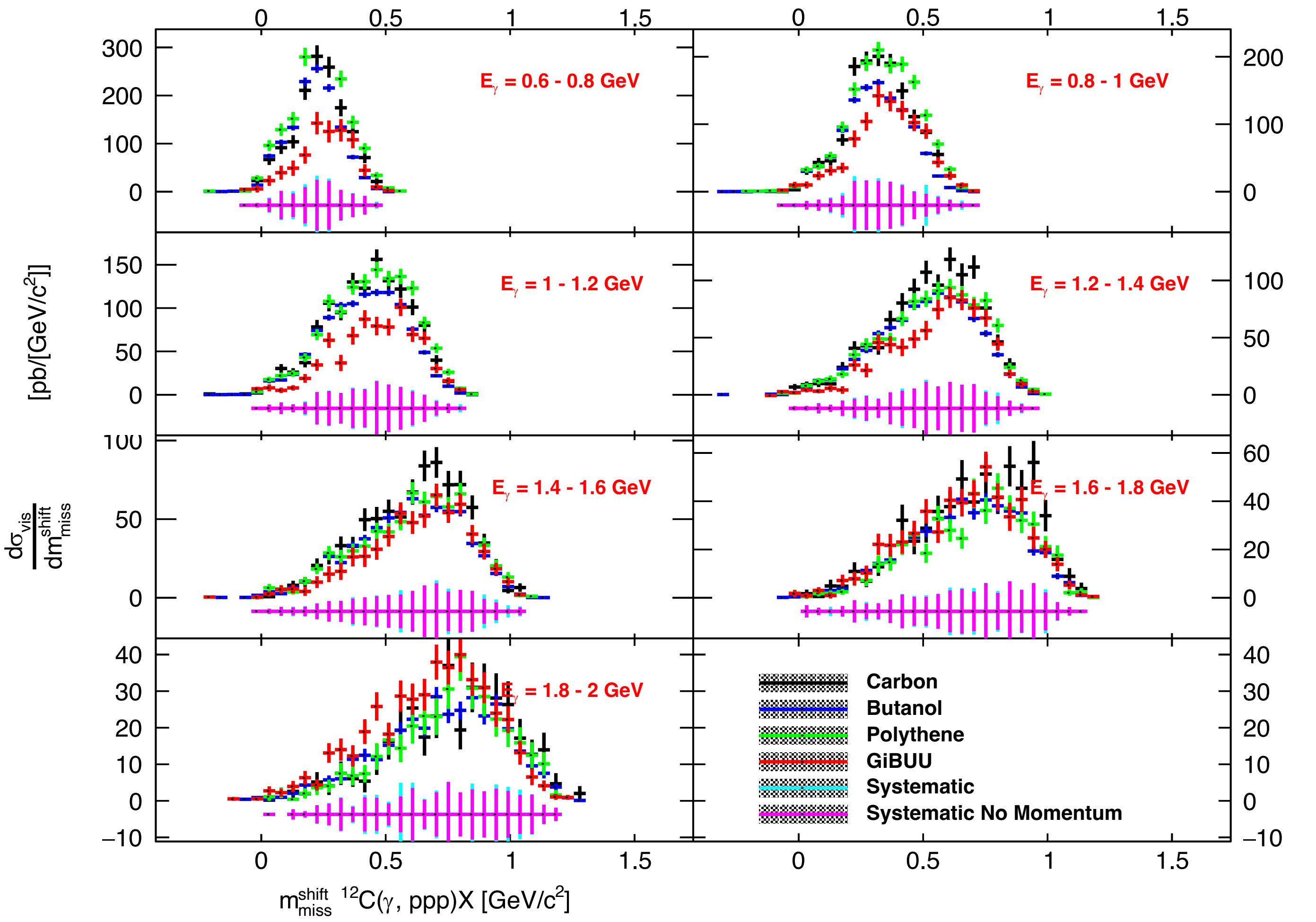

(direct) recoil fragment
$^{10}$Be (~stable)

Direct knockout yield clear but underpredicted (N*, SRC,..?)

Some features not evident in data at higher Eγ (2M modelling?)

Direct pp knockout clearly Evidenced up to ~2 GeV

# Missing mass – 3p knockout



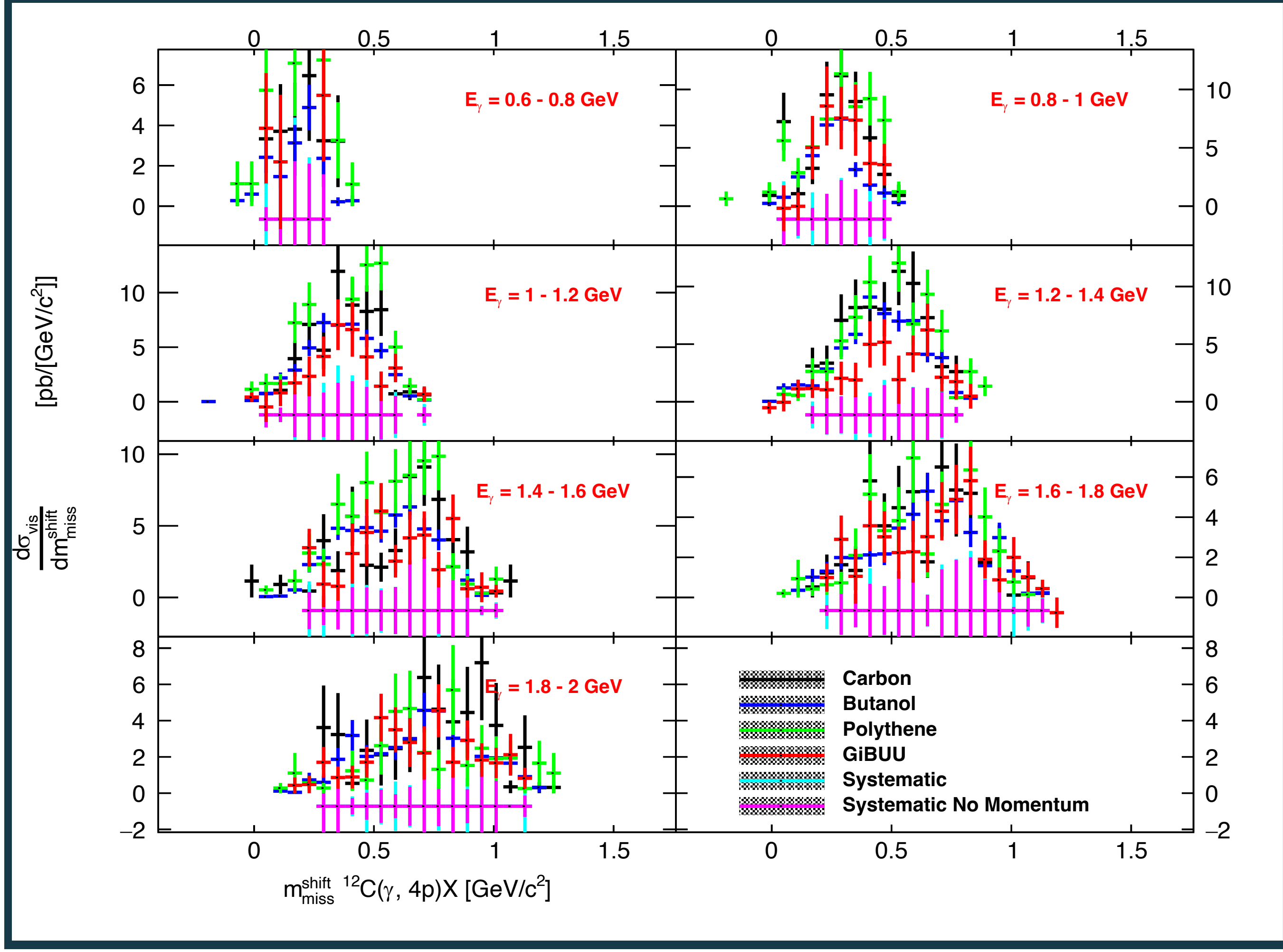

(direct) recoil fragment

$^{9}Li$ (~200ms)

Features from direct ppp Knockout observed

Tend to be underpredicted by GiBUU

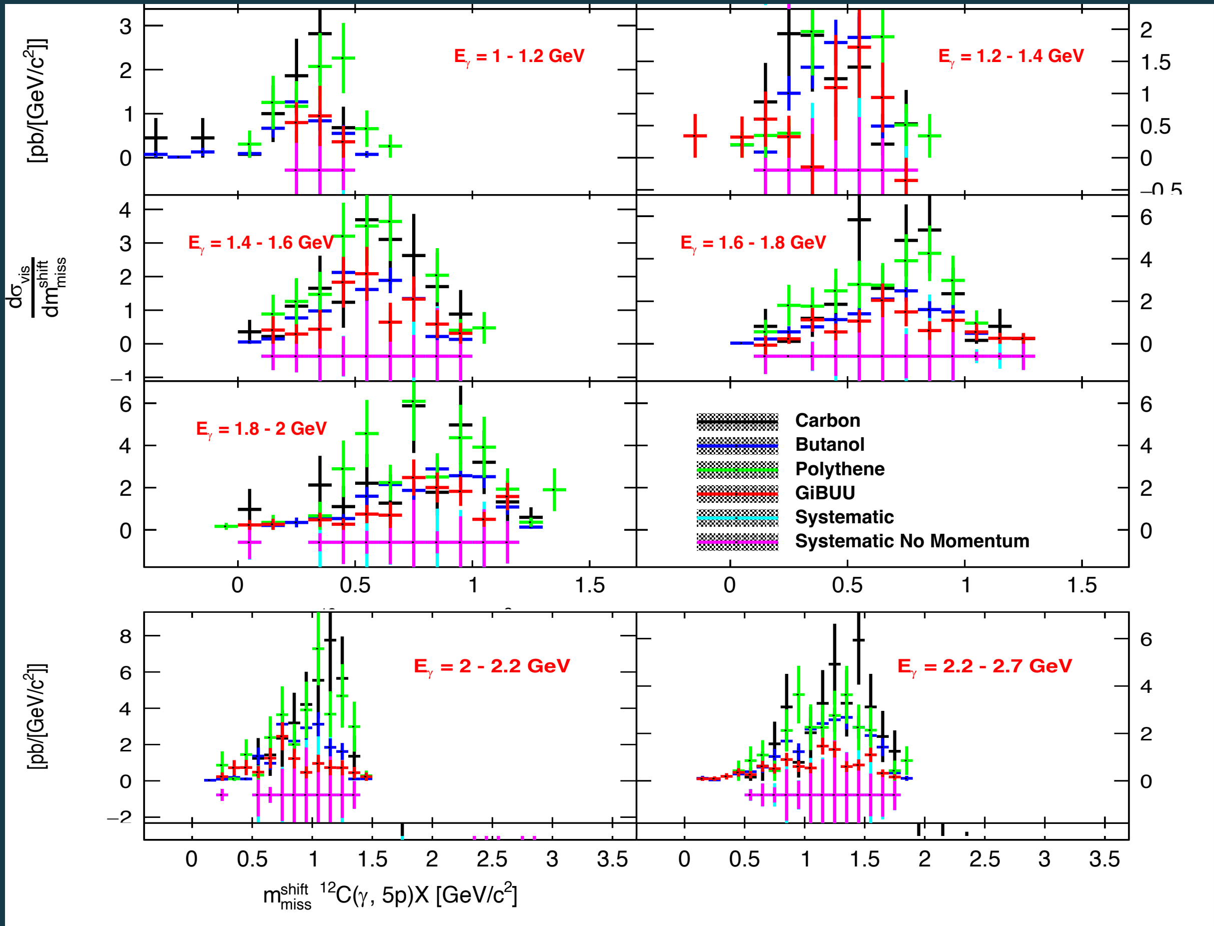
# Missing mass – 4p knockout




(direct) recoil fragment
$^{8}He$ (~119ms)

Weaker features from direct pppp knockout
GiBUU ~ agrees

# Missing mass – 5p knockout




(direct) recoil fragment

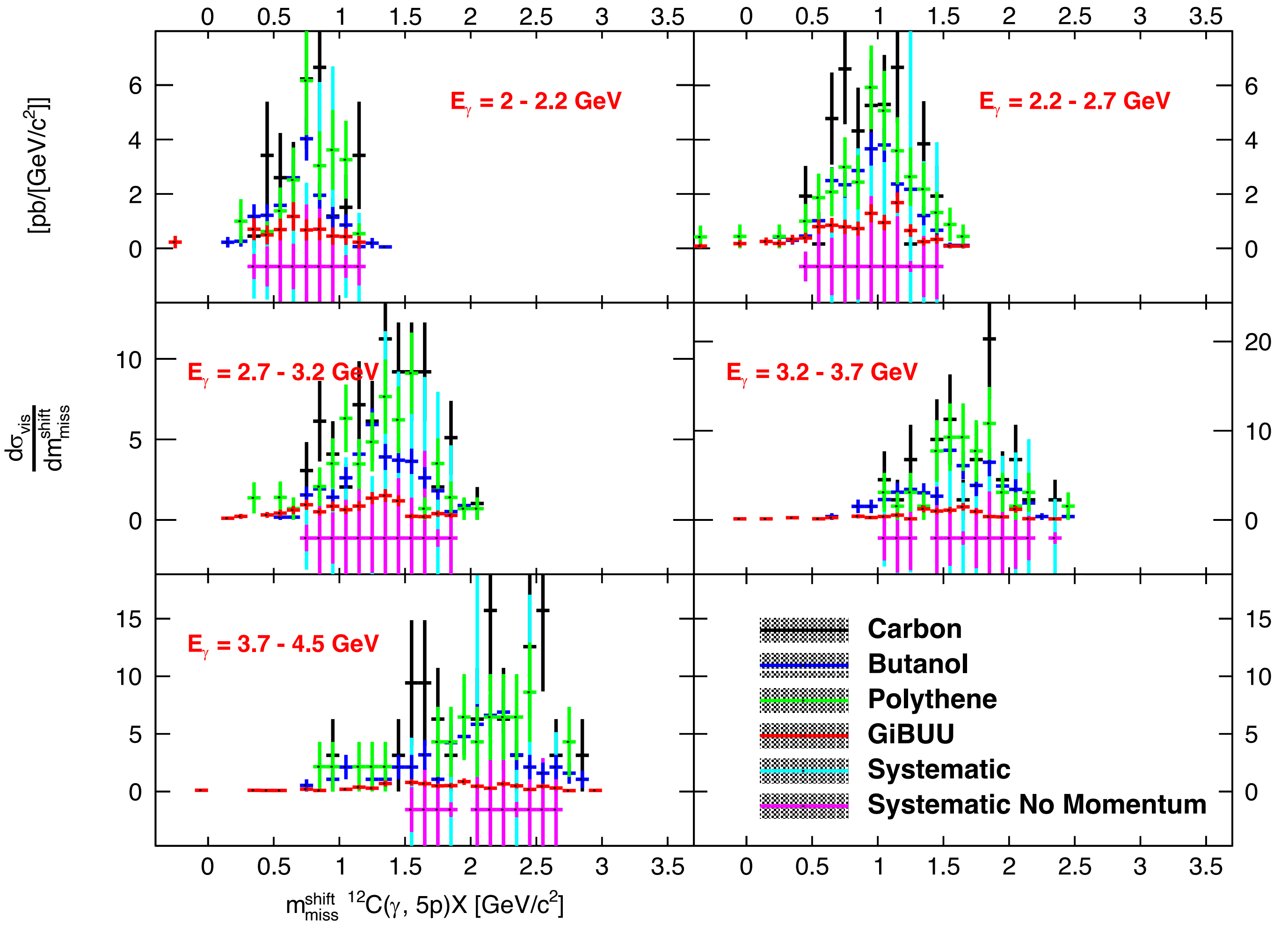
$^7H$ (~652 yattoseconds)

Broad agreement within stats

Underprediction high E$\gamma$ , $M_{miss}$

-lack of 3$\pi$ production?

# Missing mass – 6p knockout




(direct) recoil fragment

$^{6}n$ ( ??)

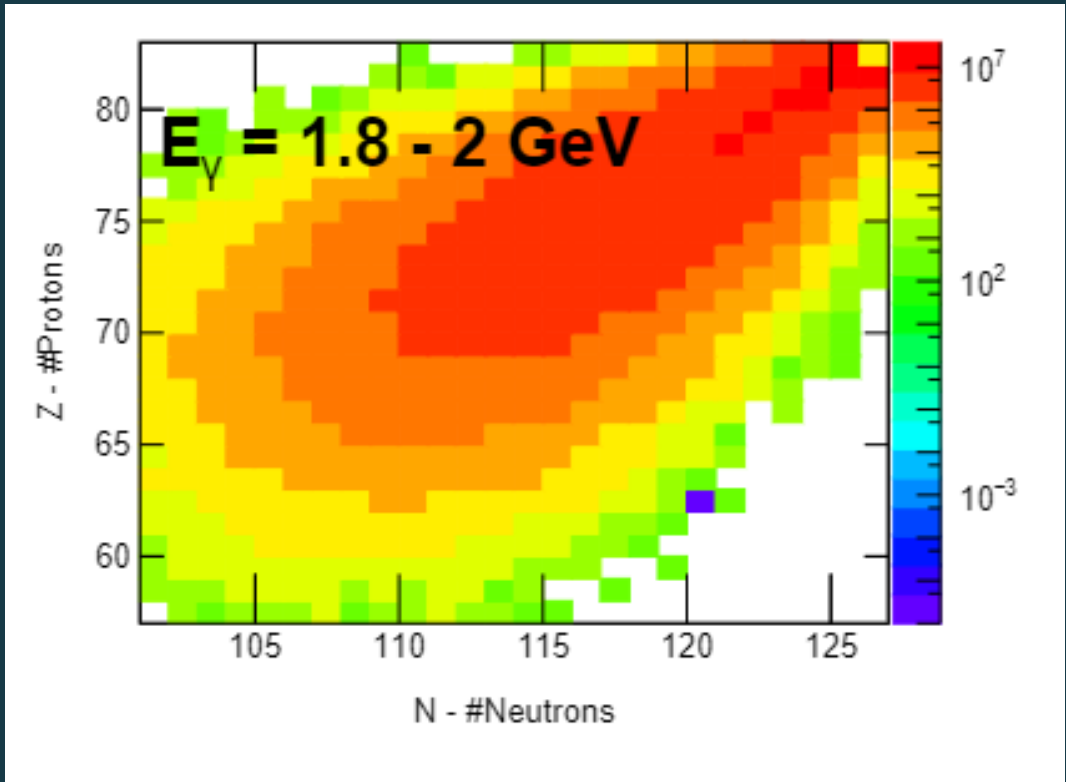
Only visible Eγ >2 GeV

- CLAS acceptance effects

GiBUU underpredicts ~factor 5

Seeded by missing 3M?

# GiBUU predictions for spallation from $^{208}$Pb target




Identify recoil ion in GiBUU (from emitted particles)

Production rates per hour with:
- Current CPS beam (~μA)
- Equivalent of 1mm Pb

Factor $10^6$ increase with 3A ER linacs
Longer targets?– factor ~$10^2$

Yield map extremes limited by current simulation statistics – currently running on computer farm ☺

**Study of electro-induced reactions**
**(CLAS12@JLAB)**

**Part of e4nu initiative – reaching kinematics closer to future neutrino faciliities**

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# E4ν – preliminary results with CLAS12 detector in Hall B

~Hermetic acceptance for scattered e⁻ (and reaction products)

Reconstruct (known) e⁻ beam energy independently from products (e.g detected proton)

Compare with GeniE, GiBUU model predictions (passed through detector acceptance )

These new 12 GeV data advance on previous CLAS6 Data with improved statistics, wider kinematic reach and first measurements with Argon targets

Article

**Electron-beam energy reconstruction for neutrino oscillation measurements**

https://doi.org/10.1038/s41586-021-04046-5
Received: 29 June 2020

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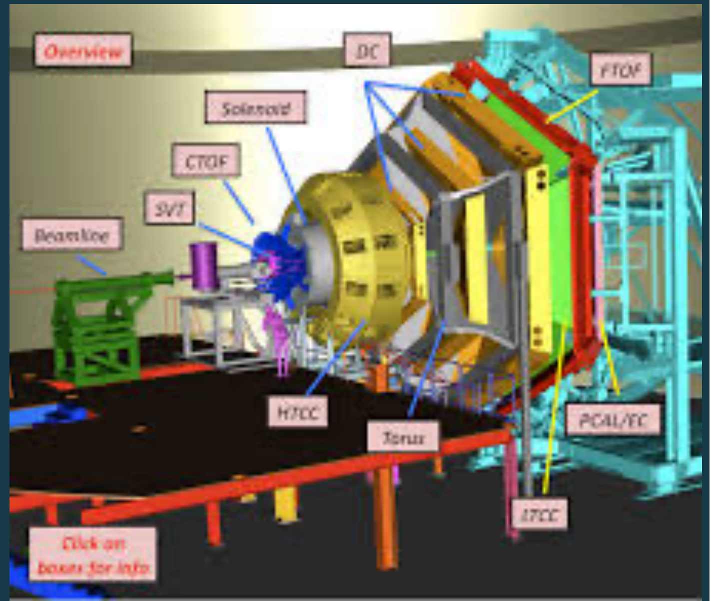
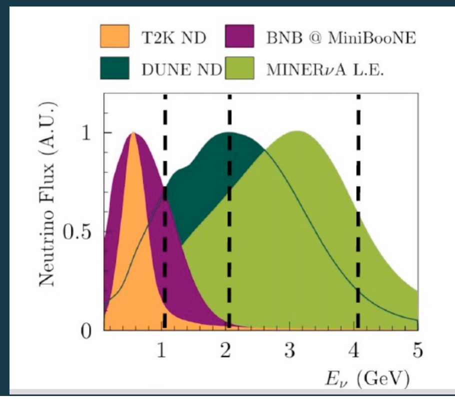
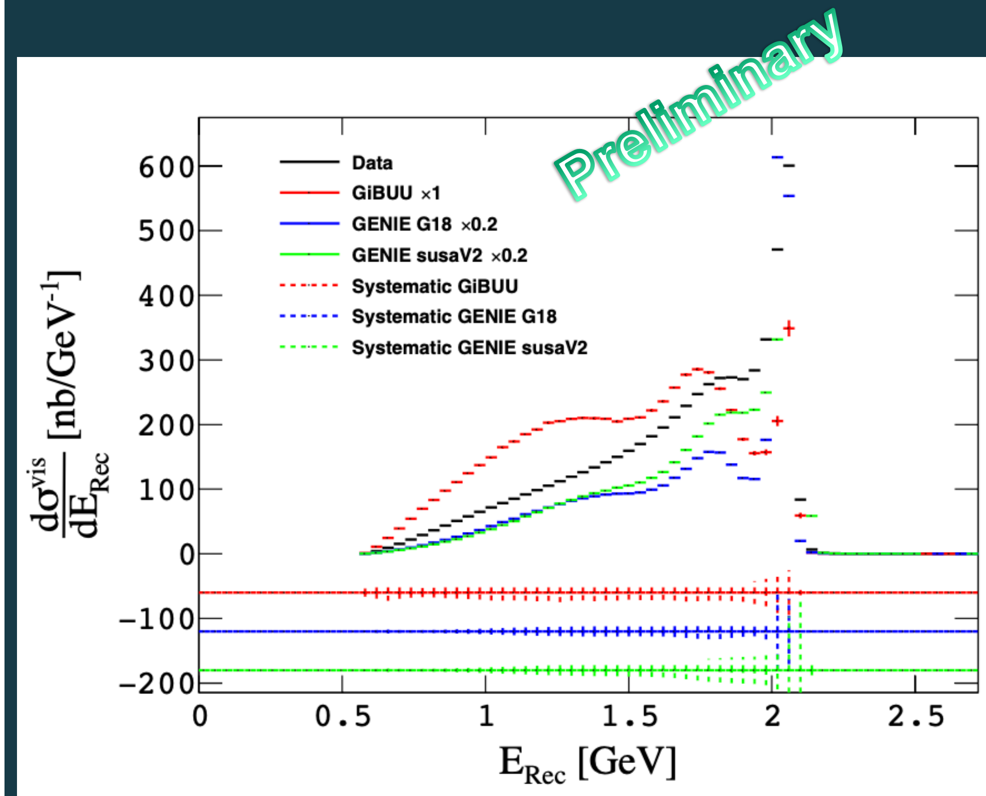
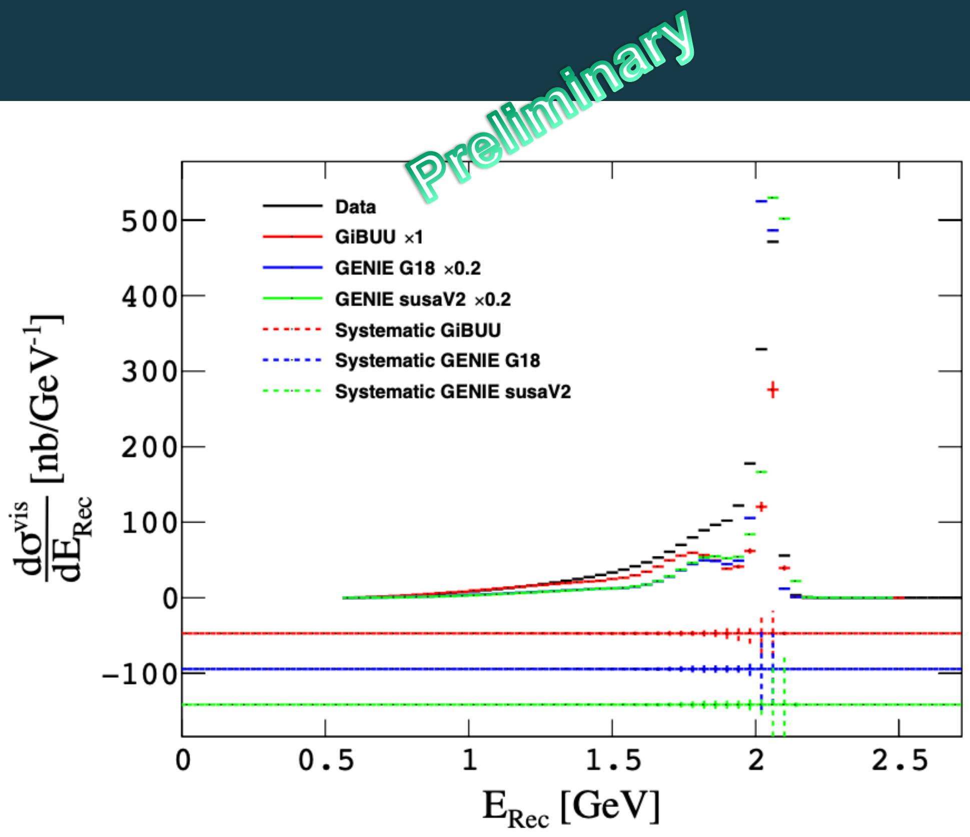


# $^{40}Ar(e,e'p)X$ 2 GeV $e^-$ beam



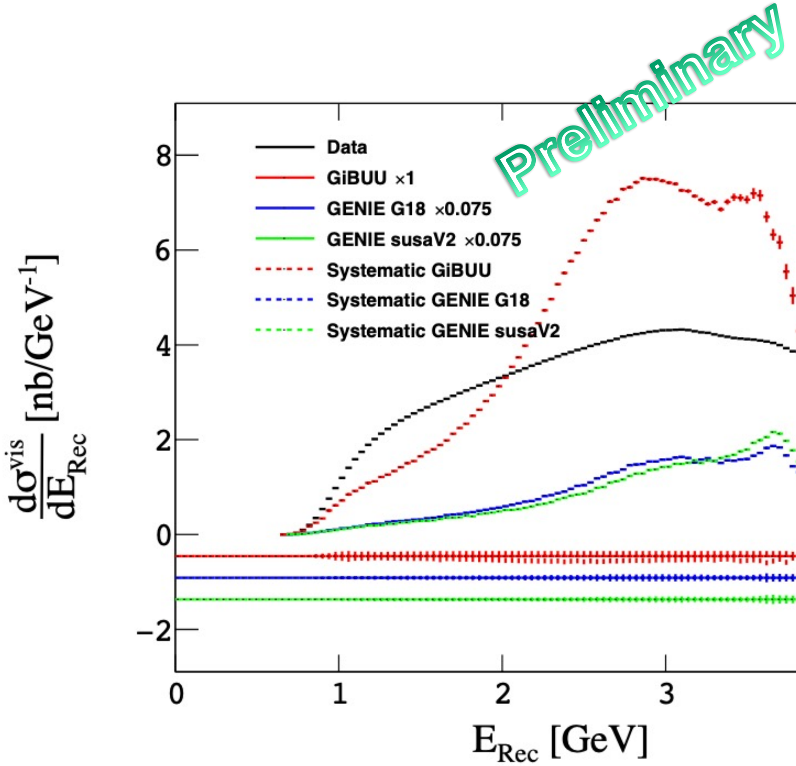

All $P^{perp}$



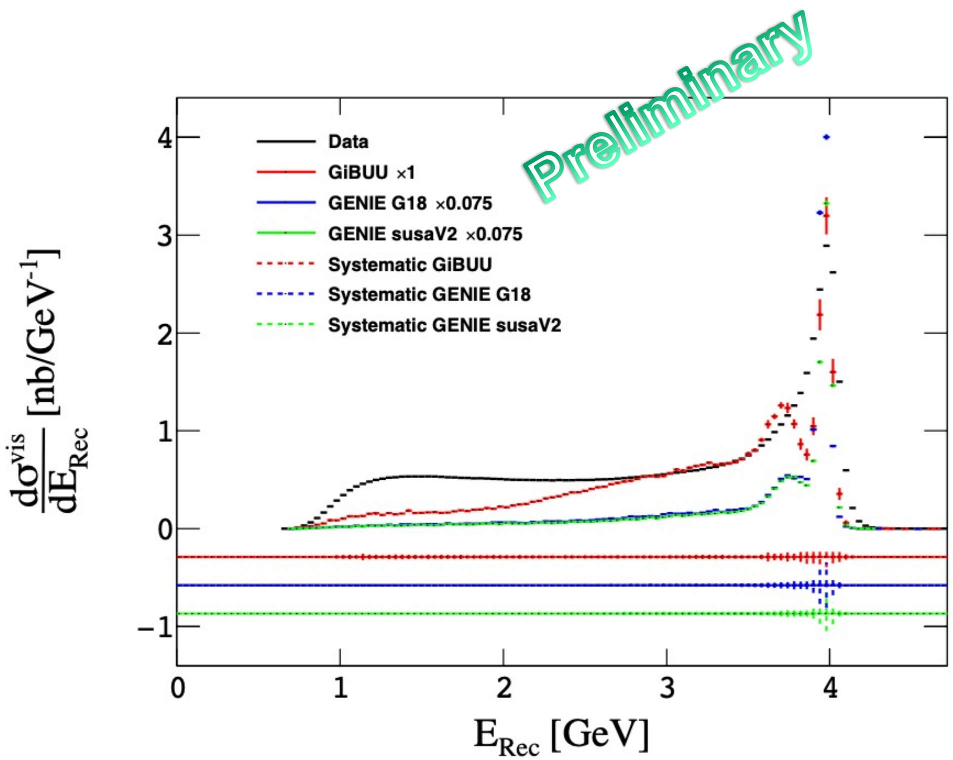

$P^{perp}$ < 0.2 GeV/c

PhD analysis Williams (York)

# $^{40}Ar(e,e'p)X$    4 GeV $e^-$ beam

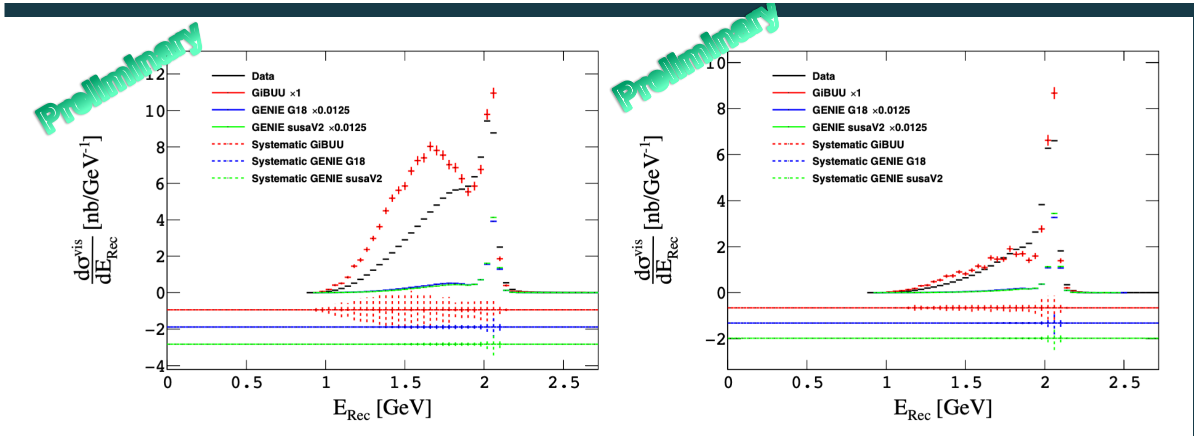



Alll $P^{perp}$

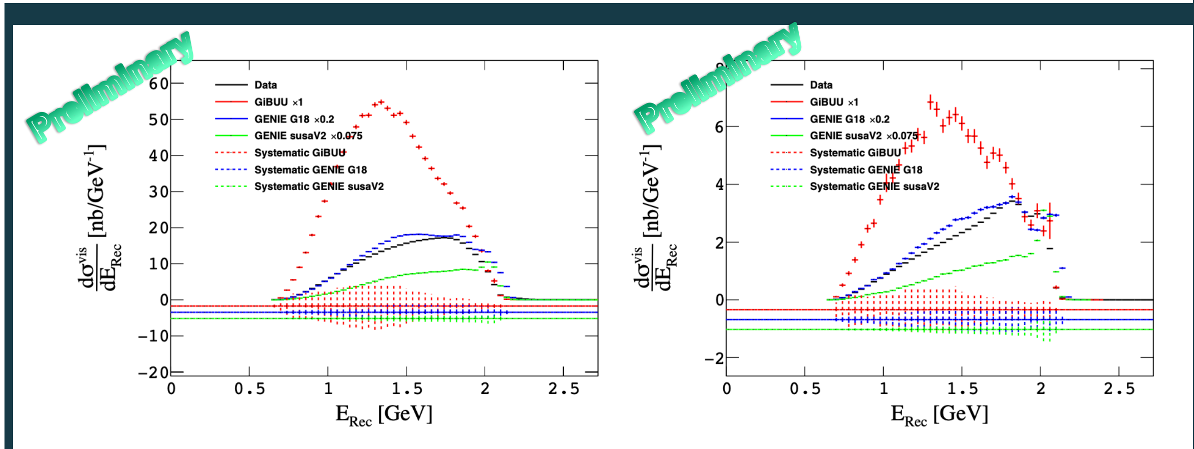



**$P^{perp}$ < 0.2 GeV/c**

PhD analysis Williams (York)




$^{40}Ar(e,e'p\pi^-)X$
2 GeV $e^-$ beam




$^{40}Ar(e,e'pp)X$
2 GeV $e^-$ beam

All $P^{perp}$ | $P^{perp}$ < 0.2 GeV/c

Plus $^{12}C$, D, targets
$p\pi\pi$, $p\pi^0$, … final states

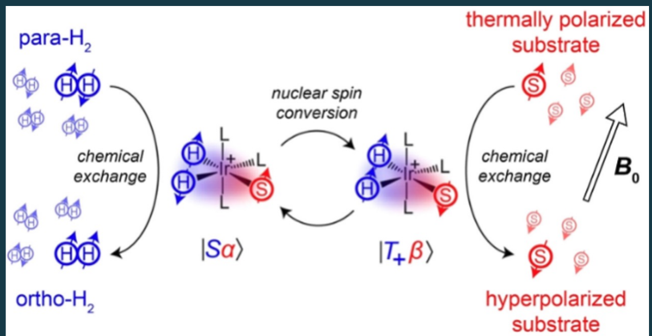
→ Extensive database to challenge models

PhD analysis Williams (York)

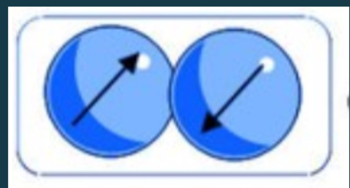
# New technologies for polarized targets

# Chemical hyperpolarisation

- Utilises a catalyst to transfer nuclear spin order from parahydrogen (singlet state of $H_2$) to target nuclei ($^1H$) by transiently binding the target substrate. (Also polarisation of D, $^{13}C$, $^{15}N$ has been demonstrated)
- Operates at room temperature
- Polarisation largely insensitive to <~10$^o$ temp changes
- ChHYP media aligns with weak applied field (earth's magnetic field if none applied !)
- York (Physics/Chemistry) -> new R&D to optimise substrates, catalysts and methods for application in nuclear and particle physics (>Volumes, >polarisation degree, <dilution, >relaxation times,..)




SABRE spin transfer



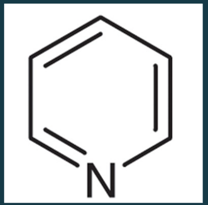
$pH_2$ spin configuration

# ChHYP substrates- baseline

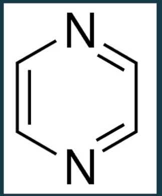
| | Pyridine | Pyrazine | 3,5-dichloropyridine |
|---|---|---|---|
| Formula | $C_5H_5N$ | $C_4H_4N_2$ | $C_5H_3Cl_2N$ |
| Fraction of protons | 5/42 = 11.9% | 4/42 = 9.5% | 3/74 = 4.1% |
| (typical) Polarisation lifetime | $T1_{Ortho}$: 6.4s<br>$T1_{Meta}$:10.4s<br>$T1_{Para}$:7.9s | $T1_{Otho/Meta}$: 13.2s | $T1_{Ortho}$: 63.6s<br>$T1_{Para}$: 116.9s |
| | | | |

Butanol used in DNP has 10/42 protons polarisable (24%)

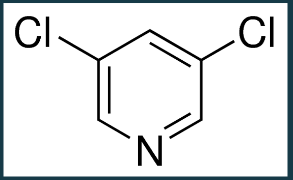
A range of substrates are being explored




Pyridine

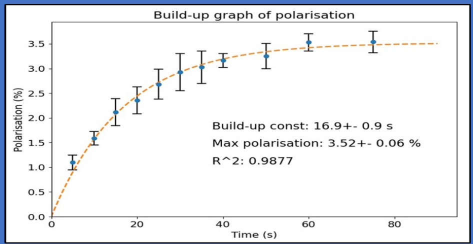


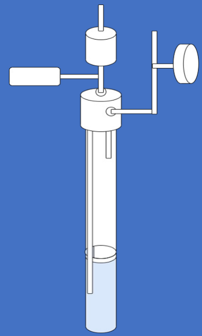

Pyrazine




3,5-dichloropyridine

## Continuous replenished polarization?



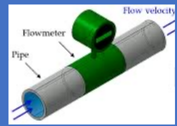



Bubbling parahydrogen
➔ Stable equilibrium polarization
➔ Enhanced by longer relaxations times – progressed from 20s to 3 minutes!

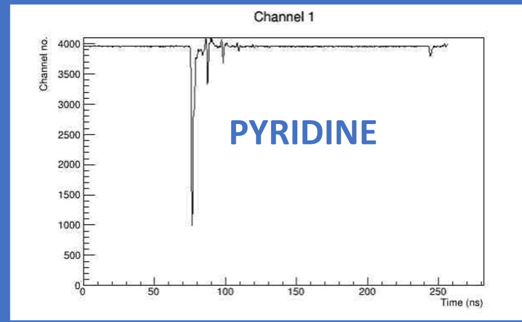
New injector systems under R&D

## Transport?

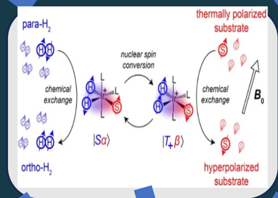
Polarised fluid can be flow in pipes without loss!




## Active polarized target?




Cerenkov visible (transparent)
10-20% iiquid scintillator doping provides viable scintillation detector
R&D ongong to polarize the scintillator!




## Radiation hardness

Cell placed in MAMI γ–beam within MRI

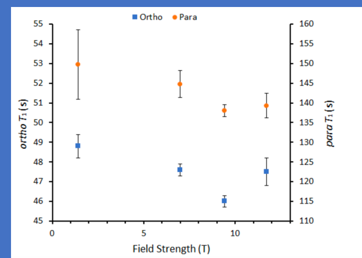
No visible effects on polarisation/relaxation

## Purfication

R&D for catalyst barriers, solvent evaporation and recovery are ongoing

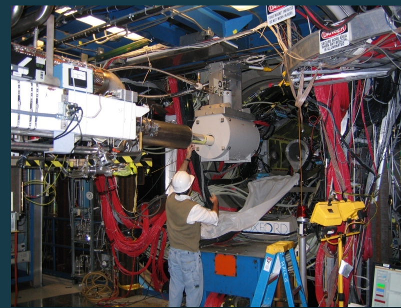
## Can it work in high B fields?

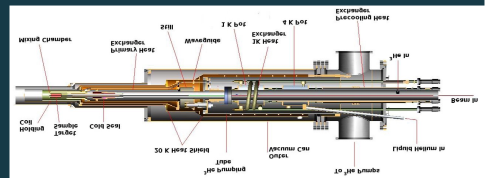
Yes!



# Potential benefits of ChHYP at scale

- At intensity frontier (e.g. CLAS12) traditional DNP fails – heat deposition radiation
- DNP is expensive (sub Kelvin cryostats, superconducting holding fields, 5T polarising magnets, ..)
- Many facilities could benefit from polarised target infrastructure but prohibitive due to cost/size.. (R3B@GSI, laser-plasma, ..,)
- The technology is very cheap - Is it scalable to much larger volume polarised detectors  (neutrino, dark matter, ..) ?
- The capability of polarising heavy (non-zero spin) nuclei is established –R&D for a polarised pellet target capability at EIC is ongoing





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# Summary

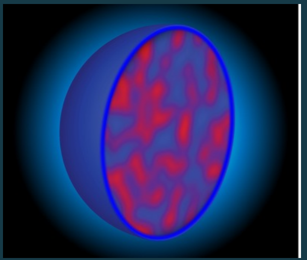
- Coh$\pi$ method for $^{208}$Pb – consistent with dipole extraction and ab-initio expectations

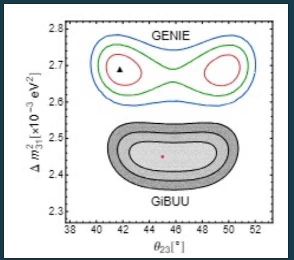
- Recent critiques do not resolve the tension with PREX

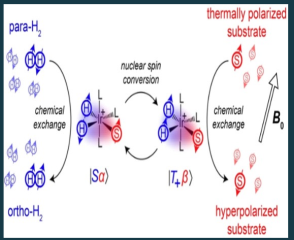
- New measurements with calcium 40/48 isotopes under analysis

- New photo and electro-induced nucleon knockout data will provide important new constraints on nuclear models for neutrino physics

- Early R&D for achieving room temperature liquid polarised target media (at scale) looks promising





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E4nu collaborations
CLAS/CLAS12 collaborations
A2 collaboration at MAMI